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Evidence for Neutrino Instability

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This Letter reports indications of neutrino instability obtained from data taken on the charged- and neutral-current branches of the reaction

$$\bar{\nu}_e + d \begin{cases} \to n + n + e^+ & (\mathrm{cc}d) \\ \to n + p + \bar{\nu}_e & (\mathrm{nc}d) \end{cases}$$

at 11.2 m from a 2000-MW reactor. These results at the (2–3)-standard-deviation level, based on the departure of the measured ratio (cc*d*/nc*d*) from the expected value, make clear the importance of further experimentation to measure the $\bar{\nu}_e$ spectrum versus distance.

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We have measured cross sections for the charged- and neutral-current branches of the interactions of fission neutrinos with deuterons:

$$\bar{\nu}_e + d \begin{cases} \to n + n + e^+ & (\mathrm{cc}d) \\ \to n + p + \bar{\nu}_e & (\mathrm{nc}d) \end{cases}. \qquad (1)$$

As described elsewhere,[1] we exposed 268 kg of D_2O to the neutrino flux from a 2000-MW reactor located 11.2 m away.

Table I is an updated summary of data listed as "mode *B*" in the work of Pasierb *et al.*,[1] including additional data in that mode. A complete reexamination of these data and data from a separate subsequent mode resulted in small changes from those informally reported earlier.

To obtain the results listed in Table I each mode was separated into several time groupings, each containing reactor-on and -off data. Reactor-associated single- and double-neutron rates were obtained for each group. From these data, the measured detection efficiencies averaged over the detector, $\langle \eta^2 \rangle = 0.112 \pm 0.009$ for double-neu-

TABLE I. Data summary for $\nu_{\mathrm{reactor}} + d$ experiment.

Mode (live days)	Observed number of neutrons	Weighted mean reactor-off events/day	On-off events/day (reactor associated)
B			
(74.0 on	1	346.2 ± 2.7	68.3 ± 4.1
47.1 off)	2	49.7 ± 1.0	3.66 ± 1.67
C			
(20.6 on	1	438.9 ± 4.8	67.8 ± 19.0
19.3 off)	2	47.4 ± 1.6	2.24 ± 2.31

tron events and $\langle\eta\rangle = 0.32 \pm 0.02$ for single-neutron events, and an estimate of the reactor-associated neutron background from the $\bar{\nu}_e + p \rightarrow n + e^+$ reaction on protons in the D_2O and in the anticoincidence detectors, we deduce the ratio of charged- to neutral-current cross sections $(\langle\bar{\sigma}_{\mathrm{cc}d}\rangle/\langle\bar{\sigma}_{\mathrm{nc}d}\rangle)_{\mathrm{expt}}$ for modes B and C. A weighted mean of the ratio for the two modes yields the final value.

The measured total singles-counting rate, R_{1n}, is related to the neutral-current, single-neutron rate $R_{1n}{}^{\mathrm{nc}d}$ by the expression

$$R_{1n} = R_{1n}{}^{\mathrm{cc}d} + R_{1n}{}^{\mathrm{nc}d} + R_{1n}{}^{\mathrm{cc}p},$$

where $R_{1n}{}^{\mathrm{cc}d}$ is the single-neutron count rate detected from cc$d$, $R_{1n}{}^{\mathrm{nc}d}$ is the single-neutron count rate due to nc$d$, and $R_{1n}{}^{\mathrm{cc}p} = (10.2 \pm 0.7)/\mathrm{d}$ is the calculated single-neutron count rate due to reaction of $\bar{\nu}_e$ on protons, and other smaller background contributions.

Let $R^{\mathrm{cc}d}$ and $R^{\mathrm{nc}d}$ be the true charged- and neutral-current rates for reactor neutrinos on deuterons. Then, $R_{2n}{}^{\mathrm{cc}d} = \langle\eta^2\rangle R^{\mathrm{cc}d}$, $R_{1n}{}^{\mathrm{cc}d} = 2(0.89) \times (\langle\eta\rangle - \langle\eta^2\rangle)R^{\mathrm{cc}d}$, and $R_{1n}{}^{\mathrm{nc}d} = \langle\eta'\rangle R^{\mathrm{nc}d}$, where $R_{2n}{}^{\mathrm{cc}d}$ is the double-neutron count rate detected from cc$d$. In addition, $\langle\eta'\rangle = 0.89\langle\eta\rangle$, where the factor of 0.89 arises from a choice of ^{3}He-counter discriminator settings to reduce the reactor-independent single-neutron background. Since the ratio of charged- to neutral-current cross sections per fission $\bar{\nu}_e$ on the deuteron is

$$r = (\langle\sigma_{\mathrm{cc}d}\rangle/\langle\sigma_{\mathrm{nc}d}\rangle)_{\mathrm{expt}} = R^{\mathrm{cc}d}/R^{\mathrm{nc}d},$$

where

$$\langle\sigma\rangle = \left[\int_{E_1}^{\infty} \sigma(E)n(E)dE\right]\left[\int_{E_1}^{\infty} n(E)\,dE\right]^{-1},$$

$n(E)$ is the neutrino spectrum, and E_1 is the energy above which we choose to measure the cross section $\sigma(E)$, we have

$$r_{\mathrm{expt}} = \frac{\langle\eta'\rangle R_{2n}{}^{\mathrm{cc}d}}{\langle\eta^2\rangle(R_{1n} - R_{1n}{}^{\mathrm{cc}p}) - 2(0.89)(\langle\eta\rangle - \langle\eta^2\rangle)R_{2n}{}^{\mathrm{cc}d}}.$$

Inserting numerical values for the two modes (B and C) and then combining the results, we find

$$r_{\mathrm{expt}} = 0.167 \pm 0.093,$$

where

$$\sigma_{r_{\mathrm{expt}}}{}^2 = \left(\frac{\partial r}{\partial R_{1n}}\right)^2 \sigma_{R_{1n}}{}^2 + \left(\frac{\partial r}{\partial R_{2n}}\right)^2 \sigma_{R_{2n}}{}^2 + \cdots.$$

We note that this ratio is determined from measurements taken concurrently and that various geometrical and instrumental stability factors cancel, including the ν flux.

We now compare this experimentally determined ratio with theoretical expectation, and so form a ratio of ratios

$$\mathcal{R} = r_{\mathrm{expt}}/r_{\mathrm{theor}}. \tag{2}$$

The denominator has some interesting properties: (a) It is independent of reactor-neutrino absolute normalization. (b) It is insensitive to the precise shape of the reactor-neutrino spectrum. (c) $\langle\sigma_{\mathrm{nc}d}\rangle$ is independent of neutrino type and, for the low-energy reactor neutrinos (<10 MeV), is purely axial vector and hence does not involve the weak mixing angle. (d) $\langle\sigma_{\mathrm{cc}d}\rangle$ depends only on the $\bar{\nu}_e$ portion of the total neutrino flux incident on the detector. (e) Assuming the standard model the ratio of the coupling constants is known to $\lesssim 5\%$.[2] As a result, a value of $\mathcal{R}$ below unity would signal the instability of $\bar{\nu}_e$ as it traversed the distance (centered in this deuteron experiment at 11.2 m) from its origin to the detector.

Evaluating the denominator by integration over the $\bar{\nu}_e$ spectrum from fission calculated by either Avignone and Greenwood[3] (AG) or Davis *et al.*,[3] (DVMS), we find

$$r_{\mathrm{theor}}^{\mathrm{AG}} = 0.44 \text{ and } r_{\mathrm{theor}}^{\mathrm{DVMS}} = 0.42,$$

and, accordingly,

$$\mathcal{R} = 0.38 \pm 0.21 \text{ or } 0.40 \pm 0.22,$$

which is a (3.0–2.7)-standard-deviation departure from unity, if it is assumed that the σ_r calculated above is representative of a normal distribution.

Having found a value for $\mathcal{R}$, we examine our other reactor data to test for consistency.

(1) An analysis of the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ measured with a different detector at the same 11.2 m distance from the reactor[4] has yielded a preliminary $\bar{\nu}_e$ spectrum for $E_{\bar{\nu}_e} > 4$ MeV. The value for $\mathcal{R}$ deduced from this spectrum, extrapolated below 4 MeV, is 0.47 ± 0.24, a 2.2-standard-deviation effect. If neutrino oscillations occur, the extrapolation of the neutrino spectrum to lower energies may be further in error and the value of $\mathcal{R}$ so deduced, slightly less.

(2) Unlike the insensitivity of $\mathcal{R}$ to the reactor-neutrino spectrum all other ratios of experimentally determined rates to predicted rates are markedly dependent on the reactor-neutrino spectrum and normalizations. For this reason we consider the precise values of these other ratios listed in Table II to be of less significance. They can, however, be used to test consistency with $\mathcal{R}$ and, to this end, data from several reactor experiments, the 11.2-m proton[4] and deuteron da-

TABLE II. Summary of results for the ratio $\langle\sigma_{\text{expt}}\rangle/\langle\sigma_{\text{theor}}\rangle$.

Distance from core center (m)	Reaction	Neutrino detection threshold (MeV)	Ratio AG spectrum	Ratio DVMS spectrum	Ratio Measured $\bar{\nu}_e$ spectrum (preliminary)
11.2	nc$d$	2.2	0.83 ± 0.13	1.10 ± 0.16	$1.3^a \pm 0.22$
11.2	cc$d$	4.0	0.32 ± 0.14	0.44 ± 0.19	0.61 ± 0.29
11.2	cc$p$	4.0	0.68 ± 0.12	0.88 ± 0.15	$\equiv 1.0$
11.2	cc$p$	6.0	0.42 ± 0.09	0.58 ± 0.12	$\equiv 1.0$
6	cc$p$	1.8	0.65 ± 0.09	0.84 ± 0.12	···
6	cc$p$	4.0	0.81 ± 0.11	1.02 ± 0.15	1.19 ± 0.27

[a]This number is uncertain because the $\bar{\nu}_e$ spectrum has thus far been measured > 4 MeV. If oscillations occur, the spectrum could be depressed below 4 MeV thus increasing this ratio.

ta mentioned above, and the 6.0-m proton data from an earlier experiment,[5] were employed.

We note that, since our measurement of the neutrino spectrum is only sensitive to $\bar{\nu}_e$, it should enable us to correctly predict the ratio for the charged-current branch. Table II indicates that the preliminary prediction for this ratio with use of the measured spectrum is 1.3 standard deviations from the expected value of unity. If the difference can be attributed to a normalization error between the two experiments, it would have no effect on the ratio $\mathcal{R}$. If, however, the difference is due to a statistical fluctuation and we choose for the charged current the most likely value consistent with the two experiments, then the ratio $\mathcal{R}$ would become 0.62 ± 0.16. We note in this case that whereas $\mathcal{R}$ has increased, its error has diminished, reflecting the greater precision of the prediction based on the measured $\bar{\nu}_e$ spectrum.

The idea of neutrino oscillations was proposed in analogy with the K^0 system by Nakagawa, Okonogi, Sakata, and Toyoda and by Pontecorvo.[6] If we so interpret these results[7] and for illustrative purposes assume only two base states to be involved,[8] then we find from the value of $\mathcal{R}$, a relationship between the allowed values of $\sin^2 2\theta$ (where θ is the mixing angle) and $\Delta = m_1^2 - m_2^2$, where m_1 and m_2 are the masses to be associated with these two states. The allowed regions are shown in Fig. 1.

In the same way, allowed regions can be drawn for each of the experiments listed in Table II.[9] In these cases, however, any conclusions are once again strongly dependent on the reactor-neutrino spectrum. For the Avignon-Greenwood spectrum there is an overlapping region consistent with all the experiments at 11.2 m but not with the >4 MeV data at 6 m. We note that small changes in the normalization of the 6-m data

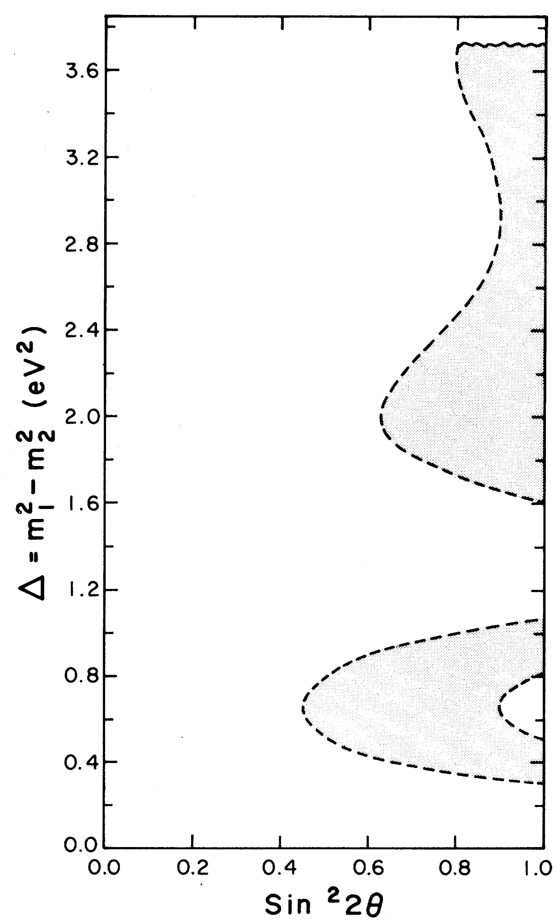

FIG. 1. Allowed regions of Δ and $\sin^2 2\theta$ for $\mathcal{R} = 0.38 \pm 0.21$.

could give agreement. This yields $0.5 \leq \sin^2 2\theta \leq 0.8$ ($32° > \theta > 22°$) and $0.7 \leq \Delta$ (eV^2) ≤ 1.0. We find that the DVMS spectrum yields no overlapping region at the level of 1 standard deviation.[10] On the other hand, it appears to predict more precisely the observed neutral-current branch of the deuteron experiment. It is evident that further experimentation with $\bar{\nu}_e$ at reactors, e.g., measurements of the $\bar{\nu}_e$ spectrum as a function of distance,[11] via the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ and further study of the reaction $\bar{\nu}_e + d$,[12] will aid in clarifying these points and provide an independent test of these preliminary indications of neutrino instability.

It would also be useful to perform experiments at accelerators and possibly with cosmic rays[13] where the higher energies would stretch out the distance scale and allow additional tests of this phenomenon.

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[1]E. Pasierb, H. S. Gurr, J. Lathrop, F. Reines, and H. W. Sobel, Phys. Rev. Lett. 43, 96 (1979); E. L. Pasierb, Ph.D. thesis, University of California, Irvine (unpublished). The thesis is available on microfilm, from University Microfilms International, Ann Arbor, Mich.

[2]R. M. Ahrens and L. Gallaher, Phys. Rev. D 20, 2714 (1979), and private communication; S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

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[4]The positron spectrum from $\bar{\nu}_e + p \rightarrow n + e^+$ was measured concurrently with the elastic scattering reaction $\nu + e^- \rightarrow \nu + e^-$. F. Reines, H. S. Gurr, and H. W. Sobel, Phys. Rev. Lett. 37, 315 (1976). Further analysis will be published elsewhere including the effect on elastic scattering of neutrino instability.

[5]F. A. Nezrick and F. Reines, Phys. Rev. 142, 852 (1966).

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[7]Theoretical aspects of low-energy neutrino interactions are discussed by H. Fritzsch, in *Fundamental Physics with Reactor Neutrons and Neutrinos*, edited by T. Von Egidy, The Institute of Physics, Conference Series No. 42 (The Institute of Physics, Bristol and London, 1978), p. 117.

[8]We note that the negative results of R. Davis [Phys. Rev. 97, 766 (1955), and private communication], who looked for $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ at a reactor and saw $< 1/50$ of that which would be produced if the reactor ν were ν_e, can be interpreted as ruling against lepton $\rightarrow$ antilepton oscillation, i.e., $\bar{\nu}_e \not\rightarrow \nu_e$ at the indicated level.

[9]We are preparing an extended discussion of possible ranges of Δ allowed by the deuteron and other data. A limit on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations is presented by S. E. Willis *et al.*, Phys. Rev. Lett. 44, 522, 903(E) (1980). Assuming maximal mixing $\Delta < 0.64$ eV^2 (90% confidence level).

[10]F. Boehm and P. Vogel, private communication. The reaction $\bar{\nu}_e + p \rightarrow n + e^+$ has been measured by Boehm, Vogel, and co-workers at 8.7 m from the 57-MW reactor of the Institut Laue-Langevin, and measurements with the same detector at larger distances from a more powerful reactor are being planned. Their e^+ spectrum is consistent with prediction based on the DVMS spectrum and on this basis does not appear to require neutrino oscillations. This conclusion is sensitively dependent on the neutrino spectrum assumed.

[11]A movable detector will be operated at the Savannah River Reactor; S. Y. Nakamura, F. Reines, H. W. Sobel, and H. S. Gurr, in *Proceedings of the International Neutrino Conference, Achen, West Germany, 1976*, edited by H. Faissner, H. Reithler, and P. Zerwas (Vieweg, Braunschweig, 1977).

[12]We continue to gather data with our deuteron detector. An experiment to study Reaction (1) is under development. T. P. Lang *et al.*, in *Neutrino-78*, edited by E. C. Fowler (Purdue Univ. Press, Lafayette, Ind., 1978), p. C68.

[13]Some evidence for oscillations of higher-energy neutrinos may have been obtained earlier in the atmos-

pheric neutrino experiments conducted in a South African gold mine. The ratio of the observed to the expected horizontal flux of product muons was determined to be $0.62^{+0.21}_{-0.12}$. F. Reines, in Proceedings of the Sixteenth International Cosmic Ray Conference, Kyoto, August 1979 (unpublished).

Breakup-Fusion Description of Massive Transfer Reactions with Emission of Fast Light Particles

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It is shown that massive transfer reactions emitting energetic light particles can be described in terms of two-step processes, in which breakup of the projectile takes place first, followed by an absorption of the massive partner of the broken-up pair by the target.

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Twenty years ago, Britt and Quinton[1] noticed that very energetic α particles are emitted rather copiously, in reactions induced by heavy ions. They are energetic in that their velocities exceed that of the projectile. More recent experiments,[2,3] which measured the coincidence of light fast particles (having $z=1$ and 2) with γ rays emitted from targetlike residues, seem to have revealed the fact that the emission of these fast particles is almost always accompanied by the fusion of the rest of the projectile into the target. Other types of coincidence experiments[4] also seem to lead to the same conclusion.

Take, as an example, the emission of fast α's observed in a bombardment of ^{159}Tb by ^{14}N.[3] If ^{10}B, the projectile minus α, is fused into ^{159}Tb, a highly excited compound nucleus ^{169}Yb is formed. This ^{169}Yb will first emit x number of neutrons, and the resultant $^{169-x}$Yb nuclei will then emit γ rays characteristic of each value of x. By measuring these γ rays in coincidence with the fast α's, one can extract the cross section of the reaction ^{159}Tb(^{14}N, α)^{169}Yb. It was found that this cross section is rather large,[3] being of the same order of magnitude as are the fast-α singles cross sections.[1] The authors of Ref. 3 called these reactions *massive transfer*. The above experimental fact shows that if once the massive transfer reaction is understood, so will be (the large part of) the emission of fast light particles.[1]

The purpose of the present Letter is to show that we can fit the data of the above experiments, based on a concept which may be termed a breakup-fusion (BF) mechanism. The name signifies that we describe the massive transfer reaction as a two-step process. Take again the above example. The first step is then the breakup of ^{14}N into $\alpha+{}^{10}$B. This is then followed by the second step, in which ^{10}B is fused into ^{159}Tb.

A general formulation of BF processes was made recently by Kerman and McVoy (KM).[5] The expression for the cross section [Eq. (27) of KM] may be written, with a slightly modified notation, as

$$d^2\sigma/dE_\alpha d\Omega_\alpha = [m_a m_\alpha/(2\pi\hbar^2)^2] \times (k_\alpha/k_a)\sum_l A_l \sum_m |\beta_{lm}(k_\alpha)|^2. \quad (1)$$

Here a ($={}^{14}$N) denotes the projectile, which is broken up into $\alpha+x$. Thus $\beta_{lm}(\vec{k}_\alpha)$ is the amplitude of the breakup process in which α is emitted with a momentum $\vec{k}_\alpha$, and x ($={}^{10}$B) with an angular momentum (lm) relative to the target A. The singles-α cross section associated with this (elastic) breakup process is given by (1), if we set $A_l=1$ (all l). If we set $A_l=P_l/4$, on the other hand, (1) gives the additional contribution to the singles-α cross section due to the BF process.[5] It can also be interpreted as the cross section of the massive transfer reaction. Here P_l denotes the penetrability between x and A, and describes the absorption of x by A.

We have reformulated the KM work and found it desirable to use

$$A_l = P_l/|s_l|^2, \quad (2)$$

in place of $A_l=P_l/4$ of KM. Thus our A_l is $4/|s_l|^2$ times that of KM. This difference originates

